Estimating the contribution from different ionospheric regions to the TEC response to the solar flares using data from the international GPS network

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Abstract

This paper proposes a new method for estimating the contribution from different ionospheric regions to the response of total electron content variations to the solar flare, based on data from the international network of two-frequency multichannel receivers of the navigation GPS system. The method uses the effect of partial shadowing of the atmosphere by the terrestrial globe. The study of the solar flare influence on the atmosphere uses GPS stations located near the boundary of the shadow on the ground in the nightside hemisphere. The beams between the satellite-borne transmitter and the receiver on the ground for these stations pass partially through the atmosphere lying in the region of total shadow and partially through the illuminated atmosphere. The analysis of the ionospheric effect of a powerful solar flare of class X5.7/3B that was recorded on July 14, 2000 (10:24 UT, N22W07) in quiet geomagnetic conditions (Dst = -10 nT) has shown that about 20% of the TEC increase correspond to the ionospheric region lying below 100 km, about 5% refer to the ionospheric E-region (100-140 km), about 30% correspond to the ionospheric F1-region (140-200 km), and about 30% to regions lying above 300 km.

Keywords

Solar Flare, GPS, ionosphere

1 Introduction

The enhancement of X-ray and ultraviolet (UV) emission that is observed during chromospheric flares on the Sun immediately causes an increase in electron density in the ionosphere. These density variations are different for different altitudes and are called Sudden Ionospheric Disturbances, SID (Davies,1990; Donnelly, 1969). SIDs are generally recorded as the short wave fadeout, SWF (Stonehocker, 1970), sudden phase anomaly, SPA (Ohshio, 1971), sudden frequency deviation, SFD (Donnelly, 1971; Liu et al., 1996), sudden cosmic noise absorption, SCNA (Deshpande and Mitra, 1972), sudden enhancement/decrease of atmospherics, SES (Sao et al., 1970). Much research is devoted to SID studies, among them a number of thorough reviews (Mitra, 1974; Davies, 1990).

Highly informative technique is the method of Incoherent Scatter (IS). The Millstone Hill IS facility recorded a powerful flare on August 7, 1972 (Mendillo and Evans, 1974a). The measurements were made in the height range from 125 to 1200 km. The increase of local electron density N_e made up 100% at 125 km altitude and 60% at 200 km.

Using the IS method Thome and Wagner (1971) obtained important evidence of the height distribution of the increase in N_e at the time of the May 21 and 23, 1967 flares. A significant increase of N_e was recorded in the E-region, up to 200%, which gradually decreases in the F-region with the increasing height, down to 10-30%, and remains distinguishable up to 300 km. The earliest increase of N_e begins in the E-region, and at higher altitudes it is observed with a delay which is particularly pronounced at F-region heights.

A sudden increase in total electron content (TEC) can be measured using continuously operating radio beacons installed on geostationary satellites. On August 7, 1972, Mendillo et al. (1974b) were the first to make an attempt to carry out global observations of the solar flare using 17 stations in North America, Europe, and Africa. The observations covered an area, the boundaries of which were separated by 70° in latitude and by 10 hours in local time. For different stations, the absolute value of the TEC increase ΔI

varies from $1.8 \cdot 10^{16}$ to $8.6 \cdot 10^{16} \mathrm{el} \cdot \mathrm{m}^{-2}$, which corresponds to 15-30% of the TEC. Investigations revealed a latitudinal dependence of the TEC increase value. At low latitudes, it was higher compared with high latitudes. Besides, the authors point out the absence of a connection between the TEC increase value and the solar zenith angle.

The advent and evolution of a Global Positioning System (GPS) and also the creation on its basis of widely branched networks of GPS stations (at least 900 sites at the August of 2001, the data from which are placed on the Internet) opened up a new era in remote ionospheric sensing. High-precision measurements of the TEC along the line-of-sight (LOS) between the receiver on the ground and transmitters on the GPS system satellites covering the reception zone are made using two-frequency multichannel receivers of the GPS system at almost any point of the globe and at any time simultaneously at two coherently coupled frequencies $f_1 = 1575.42$ MHz and $f_2 = 1227.60$ MHz.

The sensitivity of phase measurements in the GPS system is sufficient for detecting irregularities with an amplitude of up to $10^3 - 10^4$ of the diurnal TEC variation. This makes it possible to formulate the problem of detecting ionospheric disturbances from different sources of artificial and natural origins. The TEC unit (TECU) which is equal to 10^{16} $\mathrm{el} \cdot \mathrm{m}^{-2}$ and is commonly accepted in the literature, will be used throughout the text.

Afraimovich (2000a); Afraimovich et al. (2000b, 2001a,b) developed a novel technology of a global detection of ionospheric effects from solar flares and presented data from first GPS measurements of global response of the ionosphere to powerful impulsive flares of July 29, 1999, and December 28, 1999. Authors found that fluctuations of TEC are coherent for all stations on the dayside of the Earth. The time profile of TEC responses is similar to the time behavior of hard X-ray emission variations during flares in the energy range 25-35 keV if the relaxation time of electron density disturbances in the ionosphere of order 50-100 s is introduced. No such effect on the nightside of the Earth has been detected yet.

Afraimovich et al. (2001c) and Leonovich et al. (2001) suggested a technique for estimating the ionospheric response to weak solar flares (of X-ray class C). They obtained a dependence of the ionospheric TEC increase amplitude (during the solar flare) on the flare location on the Sun (on the central meridian distance, CMD). For flares lying nearer to the disk center (CMD $< 40°$), an empirical dependence of the ionospheric TEC increase amplitude on the peak power of solar flares in the X-ray range was obtained (using data from the geostationary GOES-10 satellite).

This paper is a logical continuation of the series of our publications (Afraimovich, 2000a; Afraimovich et al., 2000b, 2001a,b,c, Leonovich et al., 2001) devoted to the study of ionospheric effects of solar flares, based on data from the international GPS network.

A limitation of the GPS method is that its results have an integral character, as a consequence of which from measurements at a single site it is impossible to determine which ionospheric region makes the main contribution to the TEC variation. The objective of this study is to develop a method which would help overcome (at least partially) this problem.

2 Method of determining the shadow altitude h_0 over the ground

The method uses the effect of partial "shadowing" of the atmosphere by the terrestrial globe. Direct beams of solar ionizing radiation from the flare do not penetrate the region of the Earths total shadow. GPS stations located near the shadow boundary on the ground in the nightside hemisphere are used to investigate the solar flare influence on the ionosphere. The LOS for these stations pass partially through the atmosphere lying in the total shadow region, and partially through the illuminated atmosphere. The altitude over the ground at which the LOS intersects the boundary of the total shadow cone, will be referred to as the shadow altitude h_0.

Fig. 1 schematically represents the formation of the cone of the Earths total shadow (not to scale) in the geocentric solar-ecliptic coordinate system (GSE): the axis Z is directed to a north perpendicularly planes of an ecliptic, the axis X - on the Sun, the axis Y is directed perpendiculary to these axes. For definition of the shadow altitude h_0 it is necessary to know coordinates of a cross point C of the LOS and the shadow boundary.

The primary data are the geographical coordinates of station GPS on the Earth (Fig.1; a point P): an elevation angle and azimuth of LOS on a satellite GPS, toward the north clockwise, for the time (UT) corresponding to the phase of solar flare maximum in the X-ray range. These coordinates are converted to the Cartesian coordinate system where the Cartesian coordinates of the GPS station on the ground and the coordinates of the subionospheric point (at 300 km altitude) are calculated. Next, we use the geocentric solar-ecliptic coordinate system following the technique reported by Sergeev and Tsyganenko (1980). To determine the coordinates of the point C we solve a system of equations: the equation of cone (of total shadow), and the equation of a straight line (LOS) specified parametrically. After that, from the resulting point C we drop a perpendicular to the ground and calculate its length (Fig. 1, line h_0). The value of h_0, thus obtained, is just the shadow altitude.

3 Method of determining the TEC increase in the ionosphere using data from the global GPS net work

This paper exemplifies an analysis of the ionospheric effect of a powerful solar flare of class X5.7/3B recorded on July 14, 2000 (10:24 UT, N22W07) under quiet geomagnetic conditions (Dst = -10 nT). The time profile of soft X-ray emission in the range 1-8 Å (GOES-10 data) at the time of the flare is presented in Fig. 2a.

To determine the TEC increase in the ionosphere we used the data from the international GPS network. The GPS technology provides a means of estimating the TEC variations $I_0(t)$ on the basis of TEC phase measurements made with each of the spatially separated two-frequency GPS receivers using the formula (Calais and Minster, 1996):

$$I_0(t) = \frac{1}{40.308} \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} [(L_1\lambda_1 - L_2\lambda_2) + const + nL], \tag{1}$$

where $L_1\lambda_1$ and $L_2\lambda_2$ are the increments of the radio signal phase path caused by the phase delay in the ionosphere (m); L_1 and L_2 stand for the number of complete phase rotations, and λ_1 and λ_2 are the wavelengths (m) for the frequencies f_1 and f_2, respectively; *const* is some unknown initial phase path (m); and nL is the error in determining the phase path (m).

Input data used in the analysis include series of the oblique value of TEC $I_0(t)$, as well as corresponding series of elevations θ and azimuths of LOS to the satellite. These parameters are calculated using our developed CONVTEC program to convert standard (for the GPS system) RINEX-files received via the Internet. Input series of TEC $I_0(t)$ are converted to the vertical value following a well-known technique (Klobuchar, 1986).

$$I(t) = I_0 \cdot cos \left[arcsin \left(\frac{R_E}{R_E + h_{max}} cos\theta \right) \right] \tag{2}$$

where R_E is Earth's radius; and h_{max} is the height of the ionospheric $F2$-layer maximum.

Variations of the regular ionosphere, and also trends introduced by the motion of the satellite are eliminated using the procedure of removing the trend defined as a polynomial of the third order on a given temporary interval.

Figs. 2b and 2d present the typical time dependencies of the vertical TEC $I(t)$ for sites GPS WDLM (PRN02, shadow altitude $h_0 = 17$ km) and LEEP (PRN07, shadow altitude $h_0 = 586$ km). Time dependencies of the TEC $\Delta I(t)$ response, with the trend removed for these series, are presented in Figs. 2c and 2e, respectively.

4 Results and discussion

The TEC response to the solar flare was analyzed for 45 GPS stations. Detailed information about the GPS stations and analysis results is summarized in Table 1: names of GPS receiving stations (Site), number of the GPS satellite from which the signal is received (PRN), shadow altitude above the ground (h_0), absolute increase of TEC ΔI, relative increase of TEC ($\Delta I(t)/\Delta I_{00}(t)$, and geographical coordinates of GPS stations (latitude, longitude). The increase of TEC ΔI_{00} corresponds to the amplitude of the TEC increase measured at the station lying at the shadow boundary on the ground ($h_0 = 0$).

Fig. 3b illustrates examples of time dependencies of the TEC ΔI_0 response for LOS to the satellite which intersect the boundary of the shadow cone at different heights h_0 during the solar flare of July 14, 2000. Fig. 3b (left) presents the values of these altitudes, and (right) the names of corresponding stations. For a better visualization, the dependencies are drawn by lines of a different thickness. It should be noted that the response remains pronounced when the shadow altitude exceeds significantly the electron density peak height in the ionosphere. For station GUAM (PRN26, height of the shadow boundary $h_0 = 885$ km), the response amplitude exceeds the background oscillation amplitude by more than a factor of 2.

It is evident from Fig. 3 that the wave phase (time of the response maximum) is different at different altitudes h_0. On the one hand, this phenomenon can be caused by the interference of the response with background fluctuations; on the other, this can be due to the fact that at different heights different wavelengths of ionizing radiation are observed, which, in turn, can have independent time characteristics.

The dependence of the absolute TEC increase on the altitude h_0 for all the cases under consideration is plotted in Fig. 4a. The dependence of the relative TEC increase $\Delta I(t)/\Delta I_{00}$ on the altitude h_0 during the solar flare is shown as a percentage in Fig. 4b. The TEC increase $\Delta I_{00}(t)$ corresponds to the amplitude of the TEC increase measured at the station lying at the shadow boundary on the ground ($h_0 = 0$).

Fig. 4b suggests that about 20% of the TEC increase correspond to the ionospheric region lying below 100 km, about 5% refer to the ionospheric E-region (100-140 km), about 30% correspond to the ionospheric F1-region (140-200 km), and about 30% to regions lying above 300 km. We found that a rather significant contribution to the TEC increase is made by ionospheric regions lying above 300 km.

The estimate obtained is consistent with the findings reported by Mendillo and Evans (1974a); Mendillo et al. (1974b). The authors of the cited references, based on investigating the electron density profile in the height range from 125 km to 1200 km using the IS method, concluded that about 40% of the TEC increase during the powerful flare on August 7, 1972, correspond to ionospheric regions lying above 300 km. However, Thome and Wagner (1971), who used the IS method to investigate the ionospheric effects from two others powerful solar flares, pointed out that an increase in electron density associated with the solar flare was observable to 300 km altitude only. This difference can be explained by the fact that each particular solar flare is a unique event which is characterized by its own spectrum and dynamics in the flare process.

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